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Towards a Theory of Disciplinary Relationships: A Proposal of an Analytical Framework of Disciplinary Learning Outcome Reference Points

Satoko Fukahori*

The aim of this paper is to propose an analytical framework of disciplinary learning outcomes that will facilitate our understanding of the nature of disciplines and their relationships.

Application of the draft analytical framework, Anderson and Krathwohl's "Taxonomy of Educational Objectives" to engineering learning outcome reference points revealed the necessity for revision, by replacing the "meta-cognitive knowledge" type with what was labeled in this study as "societal/civic engagement." This new knowledge type refers to the responsibilities and contributions of engineers to society and to the wider interdisciplinary context of engineering, and reflects the contemporary attention to societal and interdisciplinary contributions of disciplines.

The revised analytical framework of disciplinary learning outcomes captured well the characteristics of engineering, a highly structured discipline with specified sets of knowledge graduates are expected to understand, but also a discipline that has traditionally focused on the application of scientific knowledge to solve problems in the real world. The established engineering competences of "basic and engineering sciences," "engineering analysis," "engineering design," "engineering practice," and "engineering generic skills" revealed to occupy particular fields on the taxonomy table, illustrating the structure of engineering learning outcomes.

The future direction of this study includes the application of the revised analytical framework to other disciplinary learning outcome reference points. By analyzing and comparing the characteristics of disciplinary learning outcomes based on a common analytical framework, we are able to capture disciplinary structures in a systematic way, and thus develop profiles of disciplines, which will provide the foundation for constructing a theory of disciplinary relationships in contemporary society.

* Kyushu University, University Education Innovation Initiative
e-mail: fukahori@ueii.kyushu-u.ac.jp

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1. Understanding the Nature of Disciplines

The sustained focus on learning outcomes-based education, or the educational approach in which programs are designed so as best to facilitate student achievement of learning outcomes, has led to the development of "learning outcome reference points" that outline the knowledge and skills students are expected to acquire as the result of their enrollment in a given educational program.

These learning outcome reference points have in part been defined in terms of generic skills, or transversal skills, that students are expected to acquire regardless of the disciplinary focus of their educational programs. Examples of generic learning outcome reference points include the Association of American Colleges and Universities' LEAP Essential Learning Outcomes (AACU, 2017), the Lumina Foundation's Degree Qualifications Profile (Lumina Foundation, 2017), the Japanese Ministry of Education's Graduate Attributes (*Gakushiryoku*) (MEXT Central Council for Education, 2008), etc.

While generic learning outcome reference points have the advantage of being applicable to a wide range of disciplines, their actual application within disciplinary contexts is by no means straightforward. What does it mean to develop critical thinking skills in literature or pharmacy, and how do we nurture communications skills in physics or history? While educational tools such as rubrics and exemplary assignments that support faculty in pursuing generic learning outcomes in disciplinary contexts, as well as faculty development opportunities, have been offered by the developers of generic learning outcome reference points, research indicates that there is still "a long way to go" in order to bring about systemic change in universities (Birtwistle et al, 2016).

Because educational programs have traditionally been organized around academic disciplines, the focus on learning outcomes-based education has also led to the revisiting of the disciplines, and to the rethinking of the role of disciplinary education in the humanizing process of the university. While few would disagree with the proposition that "a discipline represents a systematic way of organizing and studying real phenomena by the use of abstractions," there have been numerous indications that "there is no agreement among members of the academic profession about what constitutes a discipline or what the specific disciplines are" (Dressel and Marcus, 1982, pp.86-87), what knowledge and skills we expect students to acquire as the result of studying a discipline, or how a discipline can contribute to the betterment of society.

This lack of shared understanding about the nature of disciplines and their relationships with university education and to society at large is due largely to the organization of the modern university, consisting of autonomous departments in which disciplines are embedded. Protected by the principle of academic freedom, disciplinary departments have very rarely had to justify their existence by explicitly explaining to stakeholders what social contributions they have made or are capable of making, at least not until quite recently.

It is without question that the autonomy and diversity of universities must be respected. At the same time, however, if universities are to maintain their credibility, they must demonstrate that their educational programs are of good quality, as endorsed by relevant expert communities. Disciplinary communities are expected to define in their own terms what it means to be educated in the discipline, and what roles disciplinary education plays in the humanizing process of the university and in society at large. Shared understandings of the disciplines provide frameworks that universities can use as benchmarks, in order to assure that their educational programs are meeting the expectations of respective expert communities, while at the same time pursuing uniqueness through their distinctive foci.

Therefore, the collaborative development of disciplinary learning outcome reference points can be considered a major accomplishment in the history of university education. They represent shared understandings of the disciplines as of today and serve as invaluable starting points for continuous collective discussion. Examples of disciplinary learning outcome reference points include the UK Subject Benchmark Statements (QAA, 2017), the Tuning Reference Points for the Design and Delivery of Degree Programmes (Tuning, 2017), the USA Social Science Council Measuring College Learning Project's Essential Competencies (Arum et al., 2016), and the Science Council of Japan's Disciplinary Reference Points for Curriculum Design and Quality Assurance of University Education *(Bunyabetsu-Sanshokijun)* (SCJ, 2017), etc.

Furthermore, understanding the relationships among disciplines has become increasingly important, as we become increasingly aware of the complexity of problems that we face every day as the result of technological developments and globalization, of the limitations of a discipline in providing a holistic understanding of the complex world, and of the necessity of interdisciplinary solutions to complex problems (Menken and Keestra, 2016; De Greef et al, 2017). How can we effectively prepare future generations to work across disciplines as members of interdisciplinary teams? How can we effectively nurture interdisciplinary minds? How can we effectively design interdisciplinary learning experiences? Faced with the need to develop interdisciplinarity, or disciplinary integration, either at the group level or at the individual level, we are forced to identify the similarities and differences of disciplinary knowledge and disciplinary ways of thinking, and to theorize the complementary relationships of disciplines.

The need to understand not only the nature of the disciplines but also their relationships calls for a common analytical framework of disciplinary learning outcome reference points. By analyzing and comparing the characteristics of disciplinary learning outcome reference points based on a common analytical framework, we are able to grasp systematically which areas of knowledge and habits of thought are more valued and emphasized in particular disciplines. These profiles of disciplines will provide the foundation for constructing a theory of disciplinary relationships in contemporary society.

It is from this standpoint that this paper aims to propose such an analytical framework of disciplinary learning outcomes. Anderson and Krathwohl's "Taxonomy of Educational Objectives" (2001) will be applied as the draft analytical framework for two reasons. First, its dimensions of knowledge and cognitive processes are largely compatible with the components of disciplinary structure articulated in previous studies. Second, it has been proven to be a valid and effective tool for categorizing subject area educational objectives at the primary and secondary levels but has not yet been tested against disciplinary learning outcomes at the tertiary level.

The validity of the analytical framework will be tested against the engineering learning outcome reference points, which were chosen for their relative maturity and versatility. In terms of maturity, the engineers have taken the lead in developing a shared understanding of disciplinary learning outcomes, endorsed by a global network of program accreditation agencies since the late 1980s: i.e. the International Engineering Alliance's Graduate Attributes (IEA, 2017) and the European Network for the Accreditation of Engineering Education's EUR-ACE Framework Standards and Guidelines (ENAEE, 2017). Graduates of engineering programs that have been accredited by agencies within the network are considered to have acquired the learning outcomes defined in the frameworks, fulfilling the foundational requirement for becoming professional engineers in signatory countries. Having withstood the tests of time and utilization, engineering learning outcomes can be considered to be valid representations of the knowledge and skills students are expected to acquire through an engineering program.

In terms of versatility, while engineering is a highly structured discipline with specified sets of prerequisite knowledge, it is also a discipline that has traditionally focused on application, analysis, and creative problem solving. Furthermore, engineering programs are increasingly emphasizing the importance of being able to synthesize engineering knowledge and skills, as well as deliberating the role of engineers in society. Such emphases are indeed central to the learning outcomes aspired to by contemporary disciplinary education and interdisciplinary education in particular.

This paper consists of five sections. Following this introductory first section, the second section will review the literature on disciplinary structures and argue for the relevance of applying a modified Anderson and Krathwohl's Taxonomy of Educational Objectives as the analytical framework of disciplinary learning outcomes. The third section will describe how the validity of the analytical framework will be tested on engineering learning outcome reference points. The fourth section will present the results of the application. The fifth and final section will articulate implications drawn from the engineering exercise in terms of capturing the nature of disciplines and their relationships based on a common analytical framework.

2. Theories of Disciplinary Structures

2.1 Review of the Literature

As Lattuca (2001) rightly points out, because a discipline is an artifact of human thinking, structuralist and poststructuralist interpretations of the disciplines are inseparable and complementary. From the structuralist perspective, a discipline is defined as "a framework for understanding and interpreting information and experience, for judging the validity and adequacy of solutions to problems by defining what is acceptable, appropriate, and/or useful". From the poststructuralist perspective, a discipline is portrayed as "a heterogeneous social system composed of individuals with varying commitments to ideas, beliefs, and methodologies - and to one another." (Lattuca, 2001, pp.24-25) While the infrastructure of a discipline, defined by the sets of problems, methods, research practices, and the bodies of knowledge associated with them, provides important insights into the nature of disciplines, Lattuca emphasizes that structures are in themselves socially constructed, representing human ideas which are subject to constant change. This process of social construction and reconstruction of meanings that define the disciplines is vividly portrayed by Abbott (2001) in his account of sociology and the social sciences.

While fully in agreement with Lattuca regarding the significance of human agency in shaping the disciplines, and acknowledging the importance of understanding the disciplines from both structuralist and poststructuralist perspectives, this paper will nevertheless focus only on disciplinary structures, since its purpose is to capture the nature of disciplines and their relationships, as interpreted by contemporary disciplinary experts and manifested in contemporary disciplinary learning outcome reference points. It is important to note, however, that changes in the interpretation of disciplines over time can be grasped systematically by analyzing the learning outcome reference points multiple times using the same analytical framework.

Much of the work on disciplinary structures originates in the search for a theoretical basis, or the philosophy for designing the university curriculum. To Phenix (1964), "education is the process of engendering essential meanings" and "a philosophy of the curriculum requires a mapping of the *realms of meaning*, one in which the various possibilities of significant experiences are charted, and the various domains of meaning are distinguished and correlated." (Phenix, 1964, pp.5-6) Based on the analysis of the distinctive modes of human understanding which provide the foundation for all meanings, Phenix derives six fundamental realms of meaning which he claims should be covered in the university curriculum, particularly at the general education level. The six realms include: 1) symbolics (language, mathematics, and various types of nondiscursive symbolic forms, expression of meaning), 2) empirics (sciences of the physical world, empirical truths framed in accordance with certain rules of evidence and verification, analytic abstraction), 3) esthetics (various arts, perceptions of unique objects), 4) synnoetics (engagement, and relational insight), 5) ethics (moral meanings, obligation), and 6) synoptics (history, philosophy, religion, synthesis, integration).

The contribution of Phenix's early work to our understanding of disciplinary structure is the conceptualization of disciplines as established ways of understanding meanings, and the identification of six distinct patterns that are characterized by distinctively different general logical character, subject matter, representative ideas, and modes of inquiry (ibid, pp.53-54).

Building on the work of Phenix, Dressel and Marcus (1982) went beyond describing disciplinary differences to explaining them by conceptualizing five *components of disciplinary structure* which are present in all disciplines to various degrees, but whose interactions give each discipline its distinct character. The five components are 1) the *substantive component* (what the discipline relates to – subject matter or problems), 2) the *linguistic component* (a symbolism whereby particular elements can be identified and relationships defined and explored), 3) the *syntactical component* (organizing processes around which a discipline develops, modes of inquiry), 4) the *value component* (value commitments about what is worth studying and how it should be studied), and 5) the *conjunctive component* (the way in which a discipline is related to other disciplines) (Dressel and Marcus, 1982, pp.89-99).

Hence, the unique contribution of Dressel and Marcus is the identification of factors that determine disciplinary variations. In particular, Dressel and Marcus focused on *knowledge components*, separating the 1) *substantive*, 2) *linguistic*, 3) *syntactical*, 4) *value*, and 5) *conjunctive* that define the discipline.

Reflecting contemporary attention to cognitive processes, Donald (2002) focused on explaining the construct of disciplinary thinking. Based on surveys of professors' and students' perceptions of disciplinary thinking, Donald identifies five modes of inquiry that are valued to different degrees by disciplines: hermeneutics (interpretation; construction of textual meaning through a dialectic between understanding and explanation), critical thinking (a reasoned or questioning approach in which one examines assumptions and seeks evidence), problem solving (steps for formulating a problem, calculating, and verifying the logic used) , scientific method (objective methods, replicability of findings, skepticism), and expertise (well-developed representation of knowledge, action schemas). These five modes of inquiry were supported by six common thinking processes: 1) description, 2) selection, 3) representation, 4) inference, 5) synthesis, and 6) verification.

Hence, Donald's contribution to our understanding of disciplinary structure is the identification of thinking processes that shape disciplinary modes of inquiry. Disciplines differ not only in the kinds of knowledge they deal with, but also in what they value doing with the knowledge.

The development of our understanding of disciplinary structures, beginning with the identification of differences, leading to the decomposition of the knowledge dimension, and then to the decoding of the cognitive process closely parallels developments in the theories of educational objectives. Originally articulated by Bloom et al (1956), cognitive processes were conceptualized as involving knowledge, comprehension, application, analysis, synthesis, and evaluation. Note that in Bloom's taxonomy, *knowledge* and the cognitive processes of comprehension, application, analysis, synthesis, and evaluation were conceptualized uni-dimensionally.

Anderson and Krathwohl's revision to Bloom's taxonomy (2001) was the separation of the dimensions of *knowledge* and cognitive process. By introducing a two-dimensional taxonomy structure, shown in Table 1 as a matrix of the *knowledge* dimension and the cognitive process dimension, it became possible to more clearly define educational objectives, or learning outcomes, in terms of what we expect students to do with what types of knowledge.

2.2 Comparing Theories of Disciplinary Structures

Note the striking correspondence between Anderson and Krathwohl's *knowledge* dimension and Dressel and Marcus's *disciplinary components* (Table 2), as well as Anderson and Krathwohl's cognitive process dimension and Donald's thinking processes categories (Table 3). Although there are non-negligible differences in terminology, and overlaps and gaps in the categories, the tables demonstrate similarities in the basic idea of the structure of knowl-

Table 1 The Revised Taxonomy of Educational Objectives

***Knowledge* Dimension**	**The Cognitive Process Dimension**					
	Remember	Understand	Apply	Analyze	Evaluate	Create
Factual						
Conceptual						
Procedural						
Meta-cognitive						

edge and cognitive processes.

Let us first compare Anderson and Krathwohl's *knowledge* dimension and Dressel and Marcus's *disciplinary components*. Anderson and Krathwohl's knowledge types are organized in the order of abstraction, from concrete to abstract.

By *factual knowledge*, Anderson and Krathwohl refer to the basic elements that experts use in communicating about their academic discipline, understanding it, and organizing it systematically. Examples include the knowledge of scientific terms (AA) and the knowledge of major facts about particular cultures and societies (AB) (Anderson and Krathwohl, 2001, pp.45-48). This knowledge type corresponds to what Dressel and Marcus refer to as the *linguistic component* (2) and the *substantive component* (1.1).

Conceptual knowledge includes schemas, models and theories that represent knowledge about how a particular subject matter is organized and structured, how the different parts of information are interconnected and interrelated in a more systematic manner, and how these parts function together. Examples include knowledge of the variety of types of literature (BA), knowledge of the fundamental laws of physics (BB), and knowledge of the interrelationships among chemical principles as the basis for chemical theories (BC) (ibid, pp.48-52). This knowledge type is parallel to the *substantive component* (1.2-1.6) identified by Dressel and Marcus.

Procedural knowledge is the "knowing how" to do something. Examples include knowledge of the various algorithms for solving quadratic equations (CA), knowledge of the techniques used by scientists in seeking solutions to problems (CB), and knowledge of the criteria for determining which statistical procedure to use with data collected in a particular experiment (CC) (ibid, pp.52-55). This knowledge type in essence corresponds to Dressel and Marcus' *syntactical component* (3.1-3.5).

Finally, *metacognitive knowledge* refers to knowledge about cognition in general, and about one's own cognition. The focus on *metacognitive knowledge* reflects contemporary developments in research on teaching and learning which highlight the importance of making students more aware of and responsible for their own knowledge and thought. Examples include knowledge of various mnemonic strategies (DA), the knowledge that a primary source book may be more difficult to understand than a general textbook or popular book (DB), and the knowledge that one is knowledgeable in some areas but not in others (DC) (ibid, pp.55-60). Note that this is a knowledge type not addressed by Dressel and Marcus. This is to be expected, because making students more aware of their learning is a "generic" educational objective and not "discipline specific." However important, it is less likely to be articulated within the context of disciplines. Conversely, note that Dressel and Marcus' *value component* (4.1-4.5) and *conjunctive component* (5.1-5.5) have not been addressed by Anderson and Krathwohl. Given the contemporary attention to the social and interdisciplinary contributions of disciplines, this is a knowledge type that requires deliberation when proposing an analytical framework of disciplinary learning outcomes.

We will now compare Anderson and Krathwohl's <u>cognitive process</u> dimension and Donald's <u>thinking processes</u> categories. Anderson and Krathwohl's cognitive process categories are organized in the order of complexity, from lower-order thinking skills to higher-order thinking skills.

<u>Remembering</u> involves the retrieving of relevant knowledge from long term memory in the form of <u>recognizing</u> (comparing with presented information) or <u>recalling</u> (when given a

Table 2 Comparison of Disciplinary Structures – the Knowledge Dimension

Anderson and Krathwohl	Dressel and Marcus
A. Factual knowledge AA. Terminology AB. Specific details and elements.	***2. Linguistic component*** Linguistic, mathematical, nondiscursive symbols, technical language ***1. Substantive component*** 1.1 Subject matter
B. Conceptual knowledge BA. Classifications, categories BB. Principles, generalizations BC. Theories, models, structures	1.2 Assumptions, axioms, postulates 1.3 Limitations, boundaries, restrictions 1.4 Concepts, principles 1.5 Comparisons, relations 1.6 Organized knowledge
C. Procedural knowledge CA. Subject-specific skills, algorithms CB. Techniques, methods, CC. Criteria for determining when to use appropriate procedures	***3. Syntactical components*** 3.1 Principles, procedures, skills 3.2 Mode of inquiry (analysis, synthesis, evaluation, deduction, induction) 3.3 Means of collecting and evidence 3.4 Reliability of evidence 3.5 Validity of evidence
D. Metacognitive knowledge DA. Strategic knowledge DB. Cognitive tasks, appropriate contextual and conditional knowledge DC Self-knowledge	Not addressed
Not addressed *(D'. Social/interdisciplinary Knowledge)*	***4. Value component*** 4.1 Individuals (means or ends) 4.2 Truth, beauty, justice 4.3 Utility, practicality 4.4 Ethics, morals 4.5 Esthetics ***5. Conjunctive component*** 5.1 Emerging out of the preceding four 5.2 Substantive 5.3 Symbolic 5.4 Syntactical 5.5 Having values

prompt to do so). This cognitive process is essential for meaningful learning and problem solving as that knowledge, be it *factual, conceptual, procedural, or metacognitive*, is used in more complex tasks (ibid, pp.66-70).

Understanding involves constructing meaning from instructional messages, including oral, written, and graphic communication. This includes interpreting (converting information from one representation form to another), exemplifying (identifying and defining features of the general concepts or principle and using these features to select or construct a specific instance), classifying (detecting relevant features or patterns that "fit" both the specific instance and the concept or principle), summarizing (constructing a representation of the information and abstracting a summary from it), inferring (abstracting a concept or principle that accounts for a set of examples or instances by encoding the relevant features of each instance and by noting relationships among them), comparing (finding one-to-one correspondences between

Table 3 Comparison of Disciplinary Structures - Cognitive Process Dimension

Anderson and Krathwohl	Donald
1. **Remember** 1.1 Recognizing, identifying 1.2 Recalling, retrieving	Not addressed
2. **Understand** 2.1 Interpreting, clarifying, paraphrasing, representing, translating 2.2 Exemplifying, illustrating, instantiating 2.3 Classifying, categorizing, subsuming 2.4 Summarizing, abstracting, generalizing 2.5 Inferring, concluding, extrapolating, predicting 2.6 Comparing, contrasting, mapping, matching 2.7 Explaining, constructing, modeling	**Description** of context, conditions, facts, functions assumptions, and goals.
3. **Apply** 3.1 Executing, carrying out 3.2 Implementing, using	**Representation**: Organizing, illustrating, and modifying elements and relations.
4. **Analyze** 4.1 Differentiating, discriminating, distinguishing, focusing, selecting 4.2 Organizing, finding coherence, integrating, outlining, parsing, structuring, 4.3 Attributing, deconstructing.	**Selection** of relevant information and critical elements. **Inference**: Drawing conclusions, forming propositions.
5. **Evaluate** 5.1 Checking, coordinating, detecting, monitoring, testing 5.2 Critiquing, judging	**Verification**: Confirming accuracy of results, judging validity, using feedback.
6. **Create** 6.1 Generating, hypothesizing 6.2 Planning, designing 6.3 Producing, constructing	**Synthesis**: Composing wholes from parts, filling gaps, developing courses of action.

elements and patterns in one object, event, or idea and those in another object, event, or idea), and explaining (constructing and using a cause-and-effect model of a system). Because students understand when incoming knowledge is integrated with existing schemas and cognitive frameworks, and because concepts are the building blocks for schemas and frameworks, *conceptual knowledge* provides the basis for understanding (ibid, pp.66-76). This category of cognitive processes include what Donald refers to as description.

Applying involves procedures to perform exercises or solve problems, in the form of executing a familiar task (exercise) or implementing an unfamiliar task (problem solving). When executing a familiar exercise, students typically know what *procedural knowledge* to apply. When implementing an unfamiliar problem, the students must determine what *procedural knowledge* to apply, and at times make modifications to the procedural knowledge, requiring some degree of understanding of *conceptual knowledge* (ibid, pp.77-79). This category of cognitive process in essence includes what Donald refers to as representation.

Analyzing involves breaking material into its constituent parts and determining how the parts are related to one another and to an overall structure, including differentiating (determining the relevant or important pieces of a message), organizing (determining the ways in which the pieces of a message are organized) and attributing (determining the underlying purpose of the message). Analyzing is an extension of understanding and a prelude to evaluating and creating (ibid, pp.79-83). This category of cognitive process corresponds to what Donald refers to as selection and inference.

Evaluating is defined as making judgments based on criteria and standards and involves checking (judgments about the internal consistency) and critiquing (judgments based on external criteria) (ibid, pp.83-84). This category of cognitive process corresponds to what Donald refers to as verification.

Finally, creating involves putting elements together to form a coherent or functional whole. The creating process includes generating (representing the problem and arriving at alternatives or hypotheses that meet certain criteria), planning (developing a plan to solve the problem) and producing (carrying out a plan to solve a given problem that meets certain specifications) (ibid, pp.84-89). This category of cognitive process corresponds to what Donald refers to as synthesis.

2.3 Modified Analytical Framework of Disciplinary Learning Outcome Reference Points

Based on the comparisons, we are able to perceive Anderson and Krathwohl's taxonomy as a hybrid of Dressel and Marcus' and Donald's accounts of disciplinary structures, in that it combines in a two-dimensional matrix the *knowledge* and cognitive process dimensions that define the distinct characteristics of the disciplines. Hence, a review of the literature justifies applying Anderson and Krathwohl's taxonomy as the analytical framework of disciplinary learning outcomes, while highlighting the need for modification by replacing Anderson and Krathwohl's *meta-cognitive knowledge* with Dressel and Marcus' *value and conjunctive components*. As articulated earlier, while making students more aware of their learning is indeed an important educational objective, it is a "generic" one that need not be articulated within the context of discipline-based education. Understanding the disciplinary contributions to society and to other disciplines, on the other hand, is a defining component of disciplines that requires deliberation and embodying in disciplinary learning outcome statements. This alternative knowledge type will be rephrased as *social/interdisciplinary*, for easier understanding.

3. Application of the Modified Analytical Framework to Engineering Learning Outcome Reference Points

This section will describe the methodology with which the validity of the modified Anderson and Krathwohl's Taxonomy of Educational Objectives will be tested on engineering learning outcome reference points.

"A Tuning-AHELO Conceptual Framework of Expected Desired/Learning Outcomes in Engineering" (OECD, 2011) will be the subject of analysis. Consisting of five broad areas of engineering competencies, including Basic and Engineering Sciences (BES), Engineering Analysis (EA), Engineering Design (ED), Engineering Practice (EP), and Engineering Generic Skills (EGS), the framework is a synthesis of the IEA Graduate Attributes and the ENAEE EUR-ACE Framework Standards and Guidelines, and represents the shared understanding of an international engineering expert panel (Fukahori, 2014).

The validity of the modified taxonomy as the analytical framework of engineering learning outcome reference points will be examined from two perspectives. First, whether the four knowledge types, including *factual (A)*, *conceptual (B)*, *procedural (C)*, and *social/interdisciplinary (D')*, as articulated in Table 2, adequately address the range of knowledge students are expected to acquire in engineering programs. Secondly, whether the six cognitive process categories, including remember (1), understand (2), apply (3), analyze (4), evaluate (5), and create (6), as articulated in Table 3, adequately address the range of cognitive processes students are expected to engage in engineering programs. Any gaps between the taxonomy and learning outcomes will call for the reconsideration of the knowledge types, cognitive process categories, or learning outcome statements.

For this purpose, each learning outcome statement will be decoded into what students are expected to do with what types of knowledge. *Knowledge* types will be indicated in *italics* while cognitive process categories will be underlined. Corresponding *knowledge* types (*A-D'*) and cognitive process categories (1-6) will be indicated in parentheses.

Finally, mapping each learning outcome on the analytical framework according to its knowledge type and cognitive process category will enable us to discern how well the modified analytical framework fits to engineering learning outcome reference points.

4. Validity of the Modified Analytical Framework

The decoded engineering learning outcomes are presented in Table 4.

First, we examine whether the four knowledge types are represented in the engineering learning outcomes. Table 4 shows that there is a wide coverage of knowledge types, with the general pattern of BES learning outcomes addressing *factual (A)* and *conceptual (B) knowledge*, EA learning outcomes addressing *conceptual (B)* and *procedural (C) knowledge*, and EP learning outcomes addressing *procedural (C)* and *social/interdisciplinary (D') knowledge*. EGS learning outcomes focus predominantly on the *social/interdisciplinary (D') knowledge*. The knowledge types dealing with ED learning outcomes are more widespread, reflecting their integrative focus. The absence of learning outcomes addressing *meta-cognitive knowledge* justifies the modification of the analytical framework.

Second, we examine whether the six cognitive process categories are represented in the engineering learning outcomes. Table 4 shows again that there is a wide coverage of cognitive processes, ranging from understanding (2) addressed in BES, EP, and EGS learning outcomes, to applying (3), analyzing (4), and creating (6) addressed in EA and ED learning outcomes. Note the absence of remembering (1) and evaluating (5). While it is possible to assume that remembering (1) is implicitly addressed because it is to large extents a prerequisite to more complex cognitive tasks, the absence of evaluating (5) calls for attention. The cognitive processes of evaluating, including checking, coordinating, detecting, monitoring, testing, critiquing, and judging, are undoubtedly critically important competencies of engineers, particularly in light of the responsibilities and contributions of engineers to society and to wider interdisciplinary contexts. By analyzing the characteristics of the engineering learning outcome reference points, we are able to highlight the non-representation of evaluative ways of thinking and call to attention the need for a critical review.

Finally, we examine how well the modified analytical framework fits to engineering

Table 4 Decoded Engineering Learning Outcomes

Basic and Engineering Sciences	
BES1	The ability to demonstrate (2) *knowledge and understanding of the scientific and mathematical principles (A)* underlying their branch of engineering. The *basics of mathematics* include *differential and integral calculus, linear algebra, and numerical methods (A)*.
BES2	The ability to demonstrate (2) *a systematic understanding of the key aspects and concepts (B)* of their branch of engineering.
BES3	The ability to demonstrate (2) *comprehensive knowledge of their branch of engineering including emerging issues: high-level programming; solid and fluid mechanics; material science and strength of materials; thermal science: thermodynamics and heat transfer; operation of common machines: pumps, ventilators, turbines, and engines (B).*
Engineering Analysis	
EA1	The ability to apply (3) their knowledge and understanding to identify, formulate and solve (6) *engineering problems (B)* using *established methods (C)*.
EA2	The ability to apply (3) *knowledge and understanding (B)* to analyze (4) *engineering products, processes and methods (B)*.
EA3	The ability to select and apply (3) relevant *analytic and modeling methods (C)*.
EA4	The ability to conduct searches (3) of *literature (C)*, and to use (3) *data bases and other sources of information (C)*.
EA5	The ability to design and conduct (3) appropriate *experiments (C)*, interpret (4) the *data (B)* and draw conclusions (4).
EA6	The ability to analyze (4) *mass and energy balances, and efficiency of systems; hydraulic and pneumatic systems; machine elements (B)*.
Engineering Design	
ED1	The ability to apply (3) their *knowledge and understanding (B)* to develop designs (6) to meet defined and specified requirements.
ED2	The ability to demonstrate (2) an understanding of *design methodologies (C)*, and an ability to use (3) them.
ED3	The ability to carry out the design of (6) *elements of machines and mechanical systems (B)* using (3) *computer-aided design tools (C)*.
Engineering Practice	
EP1	The ability to select and use (3) appropriate *equipment, tools and methods. (C)*
EP2	The ability to combine (2) *theory and practice (B)* to solve engineering problems.
EP3	The ability to demonstrate (2) understanding of *applicable techniques and methods, and their limitations (C)*.
EP4	The ability to demonstrate (2) understanding of the *non-technical implications of engineering practice*.
EP5	The ability to demonstrate (2) *workshop and laboratory skills (C)*.
EP6	The ability to demonstrate (2) understanding of the *health, safety and legal issues and responsibilities of engineering practice, the impact of engineering solutions in a societal and environmental context, and commitment to professional ethics, responsibilities and norms of engineering practice.*
EP7	The ability to demonstrate (2) knowledge of *project management and business practices, such as risk and change management, and awareness of their limitations.*

EP8[(2)]	The ability to select and use (3) *control and production systems (B).*
Engineering Generic Skills	
EGS1	The ability to function (3) effectively as *an individual and as a member of a team.*
EGS2	The ability to use (3) diverse methods to communicate effectively with the *engineering community and with society at large (D').*
EGS3	The ability to recognize (1) the need for and engage in (3) *independent life-long learning (D').*
EGS4	The ability to demonstrate (2) awareness of the *wider multidisciplinary context of engineering (D').*

learning outcome reference points. Table 5 presents the result of the mapping exercise, where engineering learning outcomes are placed on the matrix according to their knowledge type and cognitive processes, illuminating the following two points.

First, the characteristics of the engineering discipline made visible by the mapping exercise are compatible with our general idea of engineering as a highly structured discipline with specified sets of prerequisite knowledge and a strong focus on the application of scientific knowledge to solve real life problems, supporting the effective fit of the analytical framework. While engineering learning outcomes center heavily around understanding (2) *factual (A), conceptual (B), procedural (C),* and *social/interdisciplinary (D') knowledge*, they also center on the application (3), analysis (4), and creation (6) using *conceptual (B) and procedural (C) knowledge*.

Second, the analytical framework also captures areas where engineering education has placed less value or emphasis. As articulated earlier, the mapping exercise makes visible the overall non-representation of evaluative ways of thinking (5), and in particular the absence of learning outcomes addressing engagement in complex cognitive tasks (3-6) using *social/interdisciplinary (D') knowledge*. The profile highlighted by the analytical framework can effec-

Table 5 Mapping of Engineering Learning Outcomes

Knowledge Dimension	Cognitive Process Dimension							
	Remember (1)	Understand (2)		Apply (3)		Analyze (4)	Evaluate (5)	Create (6)
Facutual (A)		BES1						
Conceptual (B)		BES2		EA2(1)		EA2(2)		EA1(2)
		BES3		ED1(1)		EA5(2)		ED1(2)
		EP2				EA6		ED3(1)
Procedural (C)		ED2(1)		EA1(1)	EA4			
		EP3		EA3	EA5(1)			
		EP5		EP1	ED2(1)			
				EP8	ED3(2)			
Social/inter-disciplinary		EP4	EGS1					
		EP6	EGS2					
		EP7	EGS3					
			EGS4					

tively inform engineers about the characteristics of engineering education, which may lead either to the revision of the engineering learning outcome reference points, or to the design of interdisciplinary programs that effectively combine engineering with disciplines that complement its weaknesses.

5. Towards a Theory of Disciplinary Relationships

The application of the modified Anderson and Krathwohl's Taxonomy of Educational Objectives, which replaced *meta-cognitive* with *social/interdisciplinary* knowledge, revealed a good fit. The modified analytical framework captured well the characteristics of engineering as a highly structured discipline with specified sets of prerequisite knowledge and a strong focus on the application of scientific knowledge to solve real-life problems. It also captured the relative overall weakness of engineering education in engaging students in evaluative ways of thinking, and in particular, in complex cognitive tasks involving *social/interdisciplinary* issues.

The future direction of this study includes the application of the modified analytical framework to other disciplinary learning outcome reference points. Preliminary analysis of pharmaceutical learning outcome reference points highlights the overwhelming emphasis of the pharmaceutical discipline on understanding factual and conceptual knowledge, with distinct focus on the application of procedural knowledge, and a heightened attention to the role of pharmacists in society.

By analyzing and comparing the characteristics of disciplinary learning outcome reference points based on a common analytical framework, we are able to grasp disciplinary structures systematically and develop profiles of disciplines which will provide the foundation for constructing a theory of disciplinary relationships in contemporary society.

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